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THESE DE DOCTORAT D'ETAT ES SCIENCES : PHYSIQUE

*présentée*

A LA FACULTE DES SCIENCES DE PARIS

*par*

Monsieur Jean GAY

*pour obtenir*

*le grade de Docteur Es-Sciences*

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*Sujet de la Thèse : Etude spectrophotométrique du Soleil  
dans l'Infrarouge lointain*

*Soutenue le 3 mars 1970 devant la Commission d'Examen*

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# Balloon Observations in the Submillimeter Region: An Absolute Measurement of the Brightness of the Sun and the Transparency of the Stratosphere above 25 km\*

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Several experiments have been successfully launched by a group involved in Infrared Space Studies at the Meudon Observatory. The present description deals with solar flights, aimed at absolute spectrophotometry of the Sun's radiation in the wavelength range from 50 to 200  $\mu$ .

The purpose of the measurements is to obtain a better determination of the solar brightness temperature in the transition zone between the photosphere and the chromosphere. The results indicate temperatures lying between the values given by the BCA model and by the recent HSRA model, in the 100 to 200  $\mu$  range. The measured temperature is  $4600^\circ \text{K} \pm 400^\circ \text{K}$ . At shorter wavelengths, the temperature seems to increase to more than  $5000^\circ \text{K}$ .

The medium-resolution spectra ( $0.5 \text{ cm}^{-1}$ ), using the Sun as a source, show submillimetric absorption lines. Because the balloon was at different altitudes (28.4 and 25 km) when the spectra were made, we can draw certain conclusions concerning the stratospheric water content. The quantity of precipitable water vapor is measured, and found to be much smaller than previous results by other authors.

The stratospheric transmission is, therefore, excellent; this opens a wide field of investigation for astronomical studies, using the stabilized gondola developed by the National Center for Space Studies (CNES).

*Key words:* Sun — stratosphere — spectroscopy

Water-vapor absorption almost completely prohibits ground-based astronomical observations at wavelengths between 23  $\mu$  and about 900  $\mu$ . Therefore this spectral region is still relatively unexplored. It is true that, in addition to the necessity for space observations, there are technical difficulties inherent to the study of submillimeter waves. However, thanks to the development of stabilized balloon gondolas and to recent progress in detectors and in submillimeter optics, it has become possible to plan an extended program of astronomical observations in this spectral region, which promises to be extremely interesting.

Fourier spectroscopy is particularly well-adapted to use in this region of the spectrum, both because of the relative ease of setting it up, and because of

the gain it affords in the signal-to-noise ratio (Felgett, 1951; Jacquinot, 1954).

The Sun is the best object on which to perfect a balloon-observation technique: first, because of the astrophysical interest inherent in the determination of its brightness temperature; and second, because it facilitates measurement of the atmospheric transmission, on which depends the future development of our observation program.

## I. The Advantage of Balloons in the Submillimeter Region

The atmospheric absorbent in this region is water vapor, whose very complex rotation spectrum contains many lines distributed in a rather uniform fashion (Turon-Lacarrieu and Verdet, 1968; Benedict, 1967). At sea-level, these lines are greatly pressure-broadened, and their wings overlap almost completely. Below 900  $\mu$ , the absorption is total, under average conditions for a low-altitude observatory. Observing from a high mountain produces

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an important gain; the lines are narrower because the pressure is lower and because — on account of the altitude and the generally low temperature — there is less precipitable water. This gain is especially noticeable at the edges of the absorption region — that is, around  $20\ \mu$  and  $1\ \text{mm}$ . However, the absorption remains almost total in the interior of this region, with the exception of a few “windows”, principally around  $350\ \mu$  (Gebbie, 1957; Farmer and Key, 1965), where the absorption is still on the order of 70%.

The gain achieved on a mountain is sufficient to have induced increasing numbers of groups to plan observations at high-altitude stations. We ourselves are arranging a station at Gornergrat (altitude  $3150\ \text{m}$ ), near Zermatt (Valais, Switzerland), in collaboration with the Observatory of Geneva and the Aeronomy Section of the CNRS (Biraud *et al.*, 1969).

In a balloon, there is a very considerable gain. This is principally connected with the decrease in pressure. The rotation lines of water vapor are still saturated for the most part, even though the quantity of precipitable water along the optical path is much less than a micron. But they are very narrow, and have little effect on the absorption when it is integrated over a great enough bandwidth (Turon-Lacarrieu, 1967).

The amount of stratospheric water vapor remains very uncertain, for many of the measurements made to date appear to have been affected by water vapor released from the balloon, the gondola, or the instrument itself. The stratosphere is generally thought to be very dry (see the discussion in Houghton, 1963). But the unpleasant experiences of other investigators whose balloon experiments have been contaminated by water vapor, inspire great caution in the planning of submillimeter observations. Frost on the optics is equally disastrous, and must be avoided at all costs.

In spite of these difficulties, the balloon is undoubtedly the ideal vehicle for observations in the submillimeter region. The residual absorption is small enough not to trouble the observations. A complex and cumbersome apparatus, including light-collectors of large dimension, can be carried in the gondola. The stabilized gondola developed by the Compagnie des Compteurs (Bizouard *et al.*, 1965) will carry a Cassegrain mirror larger than a meter in diameter. Bolometers cooled with liquid helium can also be carried. The setting precision of stabilized gondolas is equal to the demands of this type of observation.

## II. Absolute Spectrophotometry of the Sun at Submillimeter Wavelengths

According to the so-called Bilderberg Continuum Atmosphere (BCA) model of the solar photosphere, which rests on an interpretation of intensity measurements and solar limb observations in the continuum (Gingerich and de Jager, 1968), the solar photosphere has a temperature minimum of around  $4600\ ^\circ\text{K}$  throughout a rather thick layer ( $\log \tau_{5000} = -2$  to  $-3$ , corresponding to an altitude range of  $250$  to  $550\ \text{km}$ ). A more recent model (Gingerich, 1969) proposes a less pronounced temperature minimum.

The continuous radiation from this zone of minimum temperature appears in the far ultraviolet, at around  $1600\ \text{\AA}$  (Gingerich and Rich, 1968), where it seems to have been observed by Tousey and his coworkers (1963); in the medium infrared (Koutchmy and Peyturaux, 1968) between  $20$  and  $50\ \mu$ , where it was observed by Beer (1966), but without absolute calibration; at one millimeter (Noyes *et al.*, 1968); and, as recently discovered (Eddy, 1969), at  $300\ \mu$ . Labs and Neckel (1968) give a critical review of these measurements. The interpretation of the ultraviolet measurements is very complicated, even though a moderately precise measurement of the flux suffices for a good determination of the temperature in this spectral region, where the Planck function is very temperature-sensitive. The difficulty lies in the uncertainty concerning the nature of the opacity sources, the probable presence of inhomogeneities, and the debated existence of departures from local thermodynamic equilibrium for the absorbers (Gingerich and Rich, 1968; Cuny, 1968). The situation is reversed in the far infrared region: here the flux is almost proportional to the brightness temperature, which is well-determined only if the measurements are very precise. But the interpretation of the measurements is simple, for the only important opacity source known is the free-free mechanism. Thermodynamic equilibrium can be assumed, since the free electrons certainly have a maxwellian energy distribution. Therefore the measurements give the electron temperature directly.

Inhomogeneities have such a small effect at longer wavelengths, that the discrepancies between infrared and ultraviolet measurements corresponding to the same altitude should enable us to study the inhomogeneities themselves. Let  $\bar{T}$  be the mean temperature measured in the infrared, and  $\bar{B}(\nu)$  the mean brightness measured in the ultraviolet at the frequency  $\nu$ ,

corresponding to the same depth. The ratio

$$\overline{B(\nu)/B(\nu, \bar{T})} = \exp[+(h\nu/k\bar{T}) \cdot (\Delta T/\bar{T})],$$

where  $B(\nu, T)$  is the Planck function, gives information on the statistical parameters of the thermal inhomogeneities — assuming one can study this ratio over a wide enough spectral range without leaving the region under investigation.

It is therefore very desirable to test the different models proposed for the photosphere by flux measurements in the far infrared. We made the first measurements of the solar flux between 50 and 200  $\mu$ , from a balloon launched on January 16, 1968. This flight followed two others whose results were perturbed, by a technical failure during the first flight and by climatic conditions during the second.

### III. The Apparatus

We worked, then, from a balloon, and took high-resolution spectra so that we could observe the lines of residual water vapor and correct for its absorption. The measurement of the amount of residual water vapor is quite interesting in itself, for the results obtained up to now have been uncertain and often contradictory (Houghton, 1963).

The apparatus was placed in a stabilized gondola for stratospheric balloons (Fig. 1), constructed for the National Center for Space Studies (CNES) by the Compagnie des Compteurs. The gondola as a whole is free to move about its center of gravity. One of its axes is maintained horizontal by a gyro-stabilized servo-system. Pointing errors in elevation and azimuth are corrected by the coupled effects of movable weights and reaction wheels, controlled by a stationary solar sensor. The stability is of the order of  $10''$ ; the residual motions are almost random, with frequencies of less than one Hertz. However, during the third flight, the progressive descent of the balloon, due to a small leak in its envelope, produced an extraneous oscillation with a period of 15 s. We shall see below what effect this had on the spectra. This oscillation was progressively amplified until it caused the total breakdown of the guiding system, after 50 minutes of observation (Fig. 2).

The total weight of the gondola is 230 kg, including 80 kg of scientific apparatus. In our experiments, we used a 35.000 m<sup>3</sup> polythene balloon, filled with hydrogen.

The instrument (Fig. 3) is an  $f/1-f/5$  Cassegrain telescope, 40 cm in diameter, made of a cast, light alloy, covered with nickel (Kanigen process) and

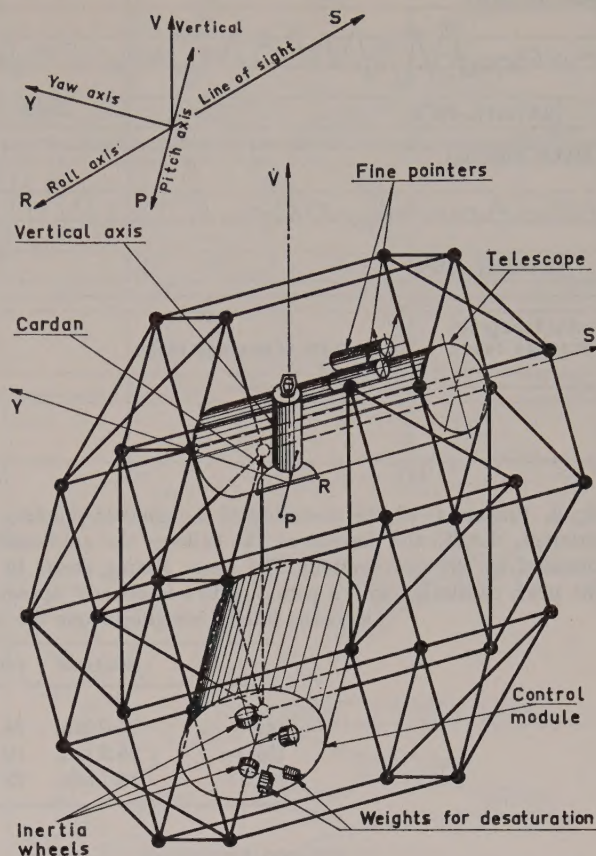


Fig. 1. General outline of the "astrolabe" gondola (illustration by the Compagnie des Compteurs). The gondola is designed to point at the Sun or at a star brighter than the fourth magnitude, with peak-to-peak setting errors no greater than  $20''$  under normal flight conditions (constant altitude greater than 30 km)

polished. The Sun is imaged on a diaphragm corresponding to an angular diameter of  $26'$ , smaller than the Sun itself in order to eliminate the effect of pointing errors. The temperature measured in the area of the diaphragm is practically equal to the mean temperature of the solar disk, for limb effects are small in the far infrared (Gingerich and de Jager, 1968).

A very compact Michelson interferometer, with a Mylar beamsplitting plate 12.8  $\mu$  thick, is located behind the diaphragm, against which is pressed a polyethylene field lens. A second polyethylene lens forms the image of the primary mirror on the quartz window of the detector. This is an ONERA pneumatic detector, constructed by the Jobin-Yvon Company, whose noise-equivalent power is on the order of  $2 \times 10^{-10} \text{ W Hz}^{-1/2}$  (Leboiteaux, 1962).

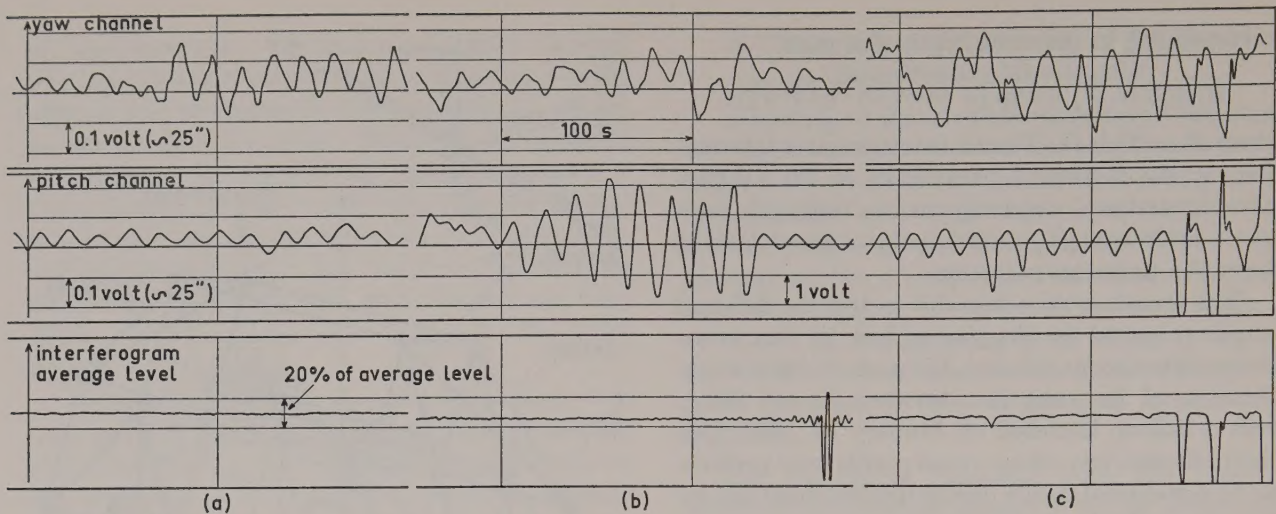


Fig. 2. Fragments of the recording of the gondola pointing errors during the third flight. At the beginning (a) of the experiment, despite the descent of the balloon, the air density is small enough for the induced perturbations to be easily corrected by the servo-system. The r.m.s. setting errors in yaw remain about  $5''$ ; in pitch the errors are a little larger. The pitch oscillation with a period of 15 s is already apparent. It grows (b) as the air density and the descent velocity increase, finally bringing about the total breakdown of the servo-system (c)

|     | Altitude | pressure | descent velocity |
|-----|----------|----------|------------------|
| (a) | 27.0 km, | 14 mb,   | 1.5 m/s,         |
| (b) | 25.2 km, | 19 mb,   | 2 m/s,           |
| (c) | 24.7 km, | 22 mb,   | 2.5 m/s          |

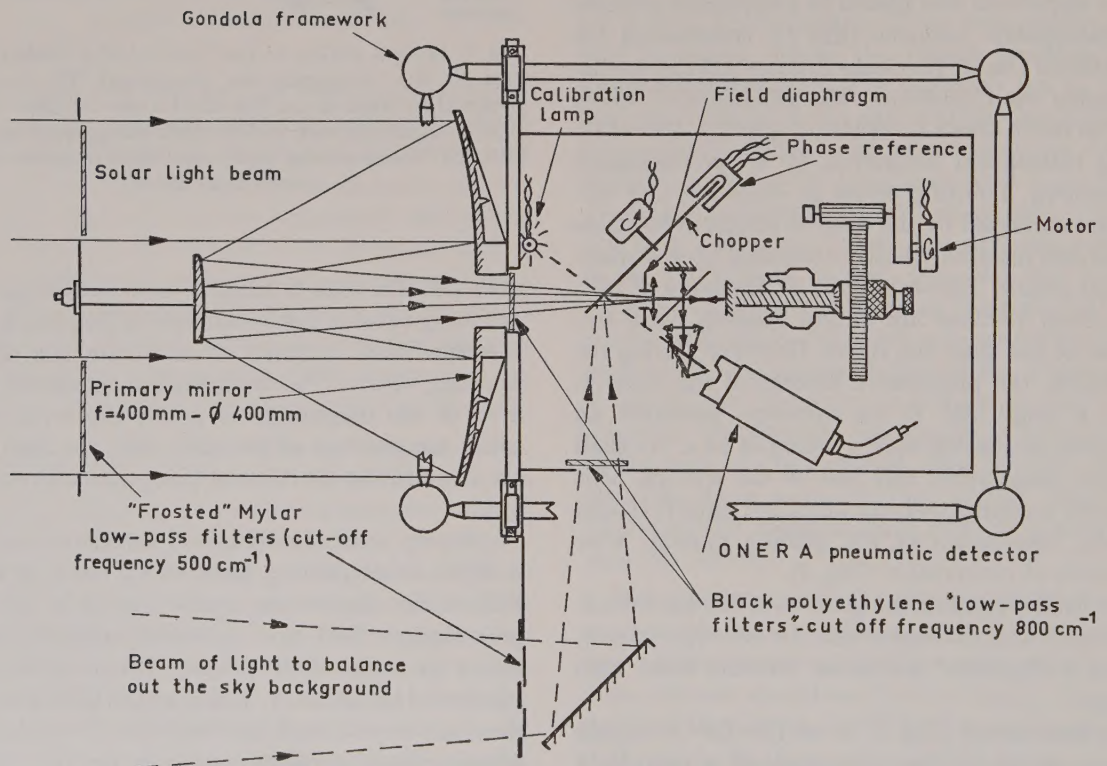


Fig. 3. General outline of the apparatus

The radiation is filtered not only by the two polyethylene lenses and the quartz window of the detector, but also by a short-wavelength diffusing filter, made of ground Mylar and placed in front of the telescope in order to prevent it from over-heating; and further, by a black polyethylene filter 100 microns thick, placed in front of the field diaphragm. Thus all radiation less than 50 microns in wavelength is absorbed.

A reflecting modulator, inclined at  $45^\circ$  to the axis of the beam, chops the solar beam coming from the telescope with a lateral beam of the same extent coming from the sky, at the rate of 12.5 Hz. This system allows us to eliminate the signal coming from the radiation of the experiment package towards the sky. It was used only during the first two flights. We shall see below why the compensation track was kept closed during the third flight, in which case the modulator chopped the Sun with the black body of the experiment package – an isothermal, absorbing box, completely closed except for the field diaphragm. The temperature of the apparatus is known to within  $5^\circ$  by telemetry. Precautions were taken to avoid radiation from the motors.

The Michelson interferometer has a continuous mechanical displacement consisting of a micrometer screw driven by a synchronous motor. The alternating current (50 Hz) is generated by the flight clock. Displacement errors with this arrangement are negligible at the wavelengths in question, as can be seen from reproducibility tests on the position of the water-vapor absorption lines (Fig. 4).

#### IV. Data Acquisition

On board the balloon (Fig. 5), the modulated signal is detected in phase and filtered in a pass-band of 1 Hz. A voltage-frequency converter transforms this signal into a pulse sequence, registered on a tape recorder aboard the balloon. The time – and thus the path difference – is marked by suppressing the pulses for 40 ms at intervals of 1 s governed by the flight clock. This corresponds to sampling the path difference every  $20 \mu$ , somewhat more frequently

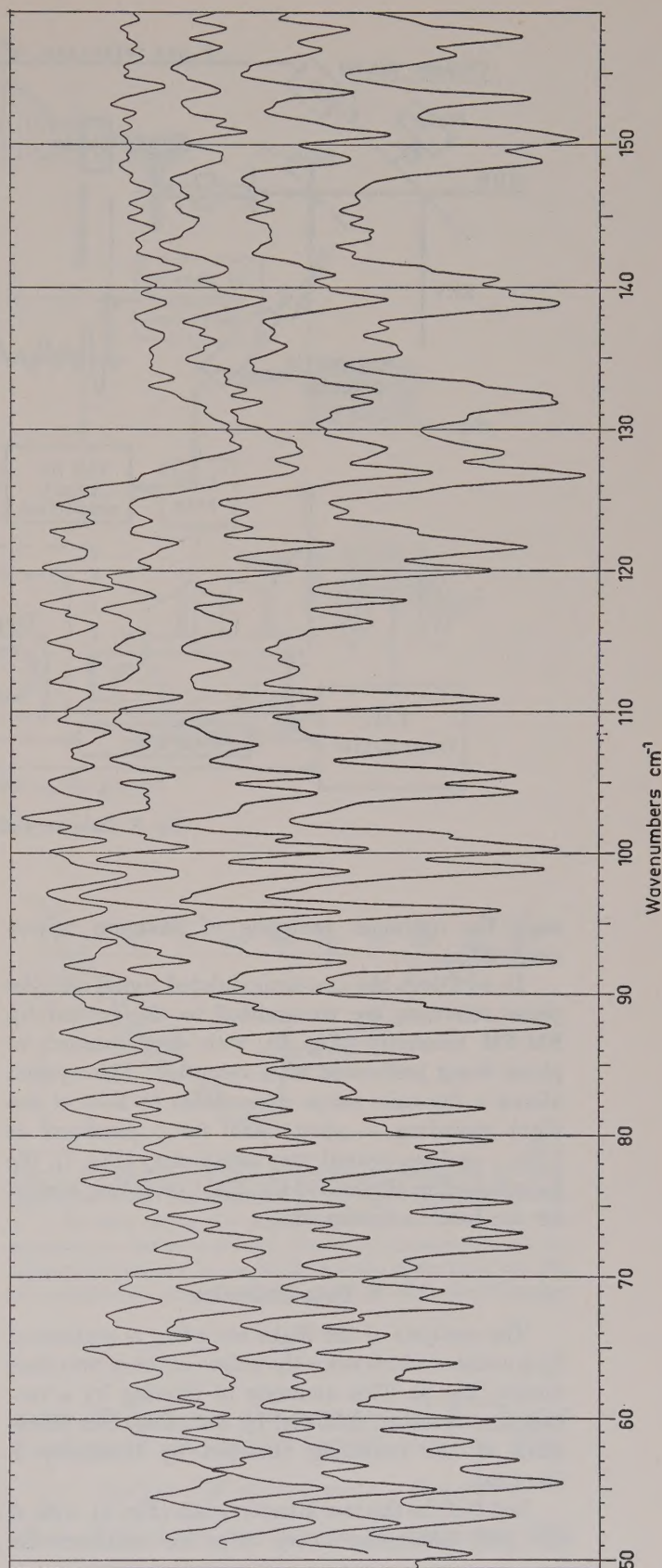


Fig. 4. Series of spectra obtained in a vacuum chamber; quantity of precipitable water increases from top to bottom. At the bottom of the diagram is drawn the theoretical spectrum of water vapor (with absorption positive), for  $0.67 \mu$  of precipitable water. Resolution  $0.5 \text{ cm}^{-1}$

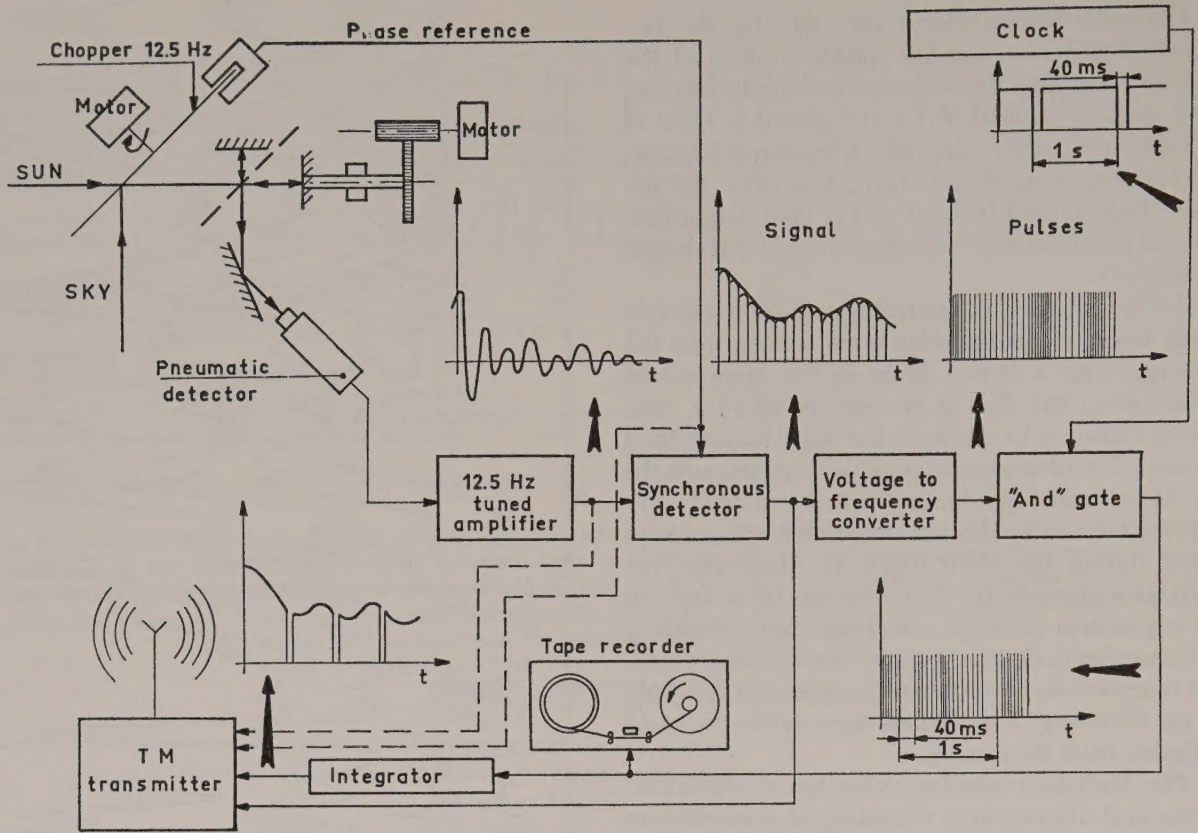


Fig. 5. Data acquisition aboard the gondola

than the optimum sampling of Shannon (about every  $22 \mu$ ).

In addition, the non-demodulated signal and the phase reference are transmitted to the ground by FM-FM telemetry (Fig. 6), with demodulation in phase being performed after reception. This system allows a dynamic range comparable to that of the flight recording — about 5000 for a passband of 1 Hz — and has proved very satisfactory (Fig. 7). We have therefore eliminated the flight recording system for our future experiments.

### V. Data Reduction

The analysis of the flight recording is performed by a counter which sums the pulses between two time marks (Fig. 8). This amounts to filtering by a rectangular function, followed by sampling. The treatment of the recording obtained by telemetry is identical.

Let  $I(\Delta)$  be the raw interferogram (Fig. 9), with  $\Delta$  the path difference. Every  $20 \mu$  we measure the

quantity

$$J_n = P \int_{\Delta = nh + \varepsilon}^{\Delta = nh + \varepsilon + l} I(\Delta) d\Delta + Q,$$

where  $h$  is the sampling interval ( $20 \mu$ ),  $n$  is the index of the point measured,  $\varepsilon$  the separation between the zero path-difference and the sampled point immediately following it,  $l$  the distance covered during one pulse-train ( $19.2 \mu$ ), and  $P$  a coefficient taking into account the sensitivity of the detector, the gain of the system, the response of the voltage-frequency converter (whose integrated response to zero is  $Q$ ), and the change of variable from time to path difference.

Then for each interferogram we calculate the mean value

$$\bar{J} = \frac{1}{M + m + 1} \sum_{n=-m}^{n=+M} J_n,$$

which is subtracted from the  $J_n$  in order to obtain a sampling of the interference alone:

$$K_n = J_n - \bar{J}.$$

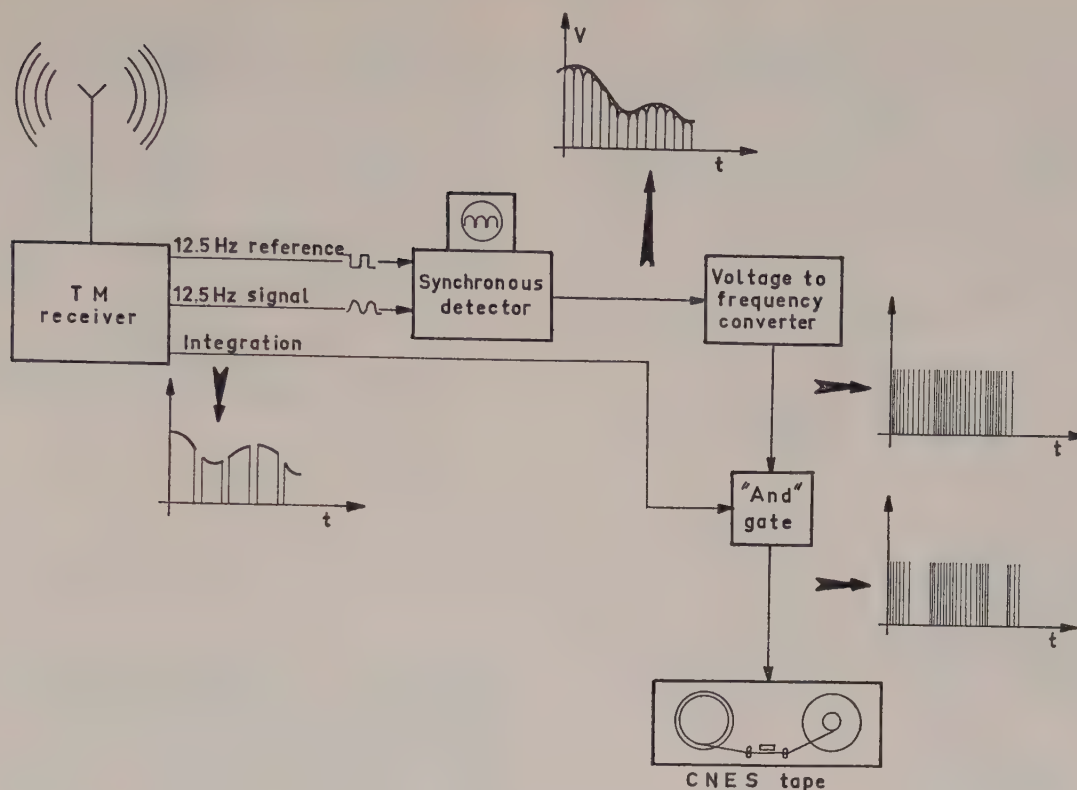


Fig. 6. Data acquisition on the ground

Thus we can calculate the values of the new interferogram at each point by Shannon's interpolation:

$$K(\Delta) = \sum_n K_n \frac{\sin(2\pi(\Delta - n\hbar - \varepsilon)/\hbar)}{2\pi(\Delta - n\hbar - \varepsilon)/\hbar}. \quad (1)$$

The summation is limited to 25 samples on either side of the zone under consideration.

*Determination of the Zero Path-Difference* (Bosomworth and Gush, 1965a)

In practice, we do not know the value of  $\varepsilon$ . Therefore we calculate a displaced interferogram:

$$K(\Delta') = \sum_n K_n \frac{\sin(2\pi(\Delta'/\hbar - n))}{2\pi(\Delta'/\hbar - n)}$$

Then we proceed to determine the value  $\varepsilon'$  that maximizes the integral function

$$f(\varepsilon') = \int K(\Delta') \frac{\sin \pi(\Delta' + \varepsilon')}{\pi(\Delta' + \varepsilon')} d\Delta',$$

in which  $p$  is chosen in such a way that the function  $(\sin \pi p \Delta)/\pi p \Delta$  is very similar to the interferogram. It can be shown that, taking into account the sym-

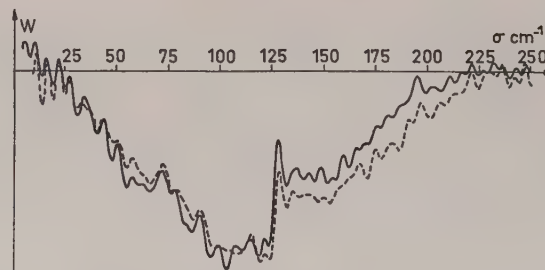


Fig. 7. Comparison between a spectrum obtained by telemetry (- -) and one obtained by the flight recording system (—). In both cases, the energies are inverted because the spectra were taken on the sky. The relative attenuation of the highest frequencies in one of the spectra arises from the difference between the pass-bands of the synchronous detectors

metry of  $K(\Delta)$  and the properties of the Fourier transform of a translated function, one can write:

$$f(\varepsilon') \propto \int B(\sigma) \cos 2\pi\sigma(\varepsilon - \varepsilon') d\sigma,$$

where  $B(\sigma)$  is the spectrum to be calculated. This

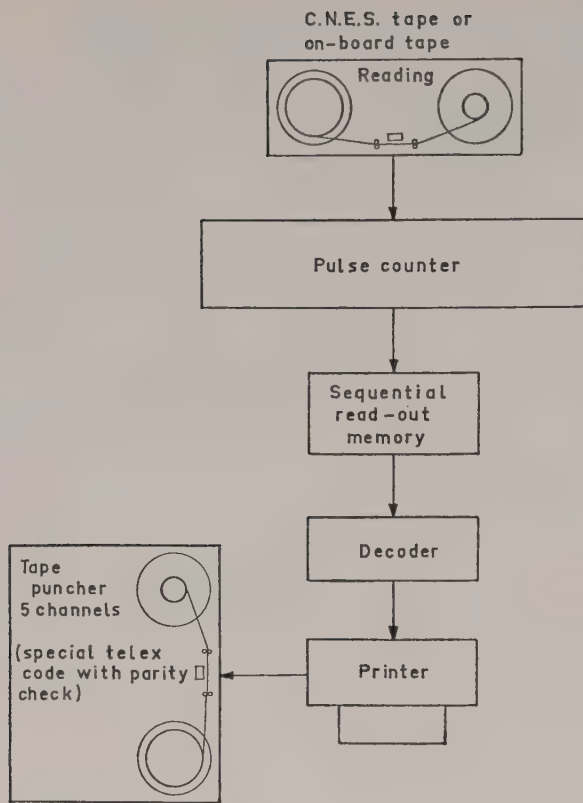


Fig. 8. Reading the magnetic tapes to prepare the data for computer processing

function is indeed a maximum for  $\varepsilon = \varepsilon'$ , since  $B(\sigma)$  is positive.

With the position of the zero path-difference determined in this way, we use Eq. (1) to calculate a new sampling centered on the origin, from which we can compute the spectrum  $B(\sigma)$ , weighting if necessary by a triangular apodizing function.

All these calculations were performed on the 7040 computer of the Meudon Observatory.

## VI. Calibration

Two completely independent calibration procedures were used. Both of them rely upon the linearity of the pneumatic detector, which is excellent up to values of the flux much greater than that recorded in our experiment (Hennerich *et al.*, 1966).

### 1. Calibration with a Black Body in the Laboratory

This calibration takes place in a vacuum chamber, in which is placed the apparatus used during the

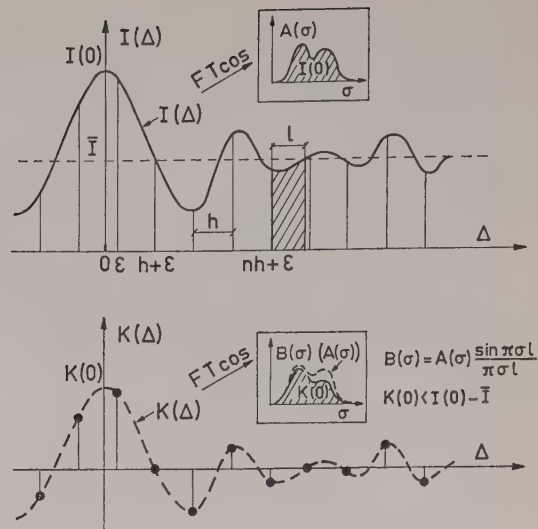


Fig. 9. Filtering effect of the sampling procedure

flight, with the corresponding filters. The telescope is pointed towards the standard black body, a conical dewar filled with liquid helium or nitrogen, whose mouth is placed at the focus of a Cassegrain collimator. The dewar is made absorbent by covering the bottom with charcoal grains and crushed glass and brick, and by totally frosting over the conical walls (Fig. 10). The beam is diaphragmed by the telescope, so that the black body, attenuated by three reflections from the collimator mirrors, is viewed in the same solid angle as the Sun. The signal after phase detection is actually the difference between the emission of the standard black body and the known emission of the box containing the interferometer, which constitutes another black body of known temperature. The thermal insulation of the box, the very absorbent interior coating, and above all the ratio between the total interior surface area (5000 cm<sup>2</sup>) and the surface area of the openings (50 cm<sup>2</sup>) guarantee that the apparatus itself forms a well-defined black body. (The motors which might heat up have been covered with a polished aluminum hood, to prevent them from radiating.)

### a) Normalization of the Spectra

The gain of the detector-electronics system is measured intermittently during the flight and during the laboratory calibration, by illuminating the detector directly with a standard incandescent lamp, using a low voltage and a very reproducible stabilized current. During the calibrations of the gain, shutters

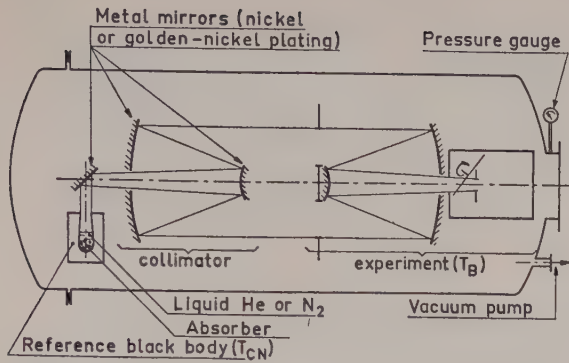


Fig. 10. Principle of the laboratory calibrations

cover the openings of the experiment box. This enables us to measure the zero energy level, after extinguishing the lamp.

The calibration signal is digitized in the same manner as the interferogram. Since the gain changes very slowly, it is sufficient to make a calibration at each end of the interferograms (every 20 minutes, in the present case). Thus there is associated with each interferogram a corresponding value  $E$  of the calibration, measured with the same gain. Each spectrum  $B(\sigma)$  is then divided by the calibration  $E$  corresponding to the interferogram from which it originates. Thus we obtain the normalized spectrum

$$b(\sigma) = B(\sigma)/E,$$

which forms the material from which the brightness temperatures will be derived.

#### b) Calculation of the Temperature of the Sun by Comparison with the Laboratory Calibrations

The signal-to-noise ratio of the calibration in the vacuum chamber, where the signal is only about 1/20 of that received during the flight, is improved by operating at low resolution and by superimposing a large number of spectra.

This method requires us to know the atmospheric transmission  $\tau(\sigma)$ , and the transmission of the collimator  $\varrho(\sigma)$ .

Then let  $b_{\odot}(\sigma)$  be the normalized solar spectrum, corrected for emission towards the sky. The solar brightness temperature  $T_{\odot}(\sigma)$  at frequency  $\sigma$  is defined by

$$b_{\odot}(\sigma) = \tau(\sigma) \cdot k(\sigma) \cdot (S \cdot \omega) \cdot [2 h c^2 \sigma^3 / (\exp(h c \sigma / k T_{\odot}(\sigma)) - 1)], \quad (2)$$

where  $k(\sigma)$  represents the total transmission of the experimental optics, and includes the coefficients introduced during data acquisition;  $(S \cdot \omega)$  is the extent of the beam admitted by the telescope; and the expression in brackets is the Planck function written in wavenumbers (with  $h$  = Planck's constant,  $c$  = the velocity of light, and  $k$  = Boltzmann's constant).

The normalized mean of the calibration spectra furnishes a standard spectrum:

$$b_e(\sigma) = \varrho(\sigma) \cdot k(\sigma) \cdot (S \cdot \omega) \cdot \left[ 2 h c^2 \sigma^3 \left( \frac{1}{e^{\frac{h c \sigma}{k T_{CN}}} - 1} - \frac{1}{e^{\frac{h c \sigma}{k T_B}} - 1} \right) \right] \quad (3)$$

This signal is produced by the difference between the energy radiated by the experiment package at temperature  $T_B$ , and that radiated by the standard black body at temperature  $T_{CN}$ , both attenuated by the effect  $\varrho(\sigma)$  of the calibration collimator.

Knowing  $T_B$  and  $T_{CN}$ , we deduce  $T_{\odot}(\sigma)$  by means of the formula

$$T_{\odot}(\sigma) = \frac{1}{2} \frac{h c}{k} \sigma + \frac{b_{\odot}(\sigma)}{b_e(\sigma)} \cdot \frac{\varrho(\sigma)}{\tau(\sigma)} \cdot \left[ T_{CN} \cdot F\left(\frac{h c}{k} \cdot \frac{\sigma}{T_{CN}}\right) - T_B F\left(\frac{h c}{k} \cdot \frac{\sigma}{T_B}\right) \right] \quad (4)$$

which we obtain by dividing Eq. (2) by Eq. (3) term by term, and expanding to second order in the Planck function for solar temperatures. The function  $F(z)$ , defined by

$$F(z) = z/(e^z - 1),$$

represents the ratio between Planck's law and Rayleigh's law, where

$$z = \frac{h c}{k} \cdot \frac{\sigma}{T}.$$

#### 2. Calibration on the Sky Background

During the flight, the telescope is offset and a spectrum is taken of the sky background in the vicinity of the Sun. The sky, whose very weak emission is due entirely to residual water vapor, thus serves as a standard black body at a temperature of 0°K. The experiment package emits like a black body at a temperature known by telemetry. The sky is observed under the same conditions as the Sun but over a larger effective solid angle, for with our equipment the detector receives energy coming from a region surrounding the secondary mirror of the telescope. The ratio of the effective solid angles (that

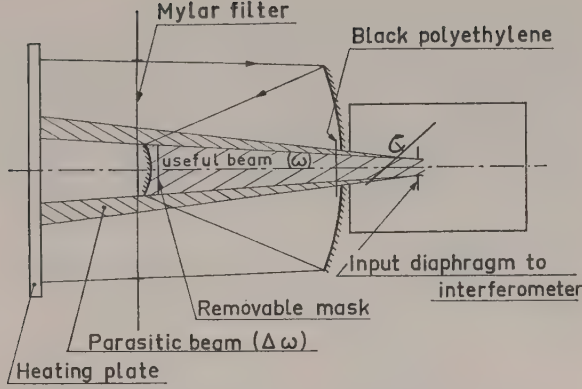


Fig. 11. Principle of measurement of the ratio between the extents of the two beams

is, including reflections from the mirrors) is determined in the laboratory at various wavelengths, by measuring in a vacuum chamber the flux received from a large, uniformly-heated surface — first with the telescope unmodified, and then with the secondary mirror exactly covered by an absorbing screen at the same temperature as the interferometer box (Fig. 11).

The use of baffles could have avoided this difficulty, which we did not foresee because the second calibration procedure was not planned at the time we designed the experiment.

In principle, this method also requires a knowledge of the atmospheric absorption and emission — the latter can be deduced from the absorption and the temperature, since the water vapor is in thermodynamic equilibrium.

The solar temperature  $T_{\odot}(\sigma)$  is then derived by a calculation equivalent to that of Eq. (4), replacing  $\varrho(\sigma)$  by the ratio of the effective solid angles

$$(\Delta\omega + \omega r^2(\sigma))/\omega r^2(\sigma),$$

where  $r(\sigma)$  is the reflection coefficient at frequency  $\sigma$  of the surface of the telescope mirrors,  $\omega$  is the solid angle of the telescope aperture, and  $\Delta\omega$  is the solid angle of the extraneous annular beam.

Moreover, the quantities in Eq. (4) referring to the standard black body must be replaced by those referring to the sky background. Thus  $T_{CN}$  is replaced by zero if there is no absorption by the atmosphere; or, if there is, by the temperature of the atmosphere  $T_a$  multiplied by the absorption coefficient

$$a(\sigma) = 1 - \tau(\sigma).$$

Thus we obtain the general expression:

$$T_{\odot}(\sigma) = \frac{1}{2} \frac{\hbar c}{k} \sigma + \frac{b_{\odot}(\sigma)}{b_{sky}(\sigma)} \cdot \frac{1 + \frac{1}{\tau^2(\sigma)} \frac{\Delta\omega}{\omega}}{\tau(\sigma)} \cdot \left[ T_a(1 - \tau(\sigma)) \cdot F\left(\frac{\hbar c \sigma}{k T_a}\right) - T_B \cdot F\left(\frac{\hbar c \sigma}{k T_B}\right) \right]. \quad (5)$$

#### a) The Effect of Atmospheric Absorption

For simplification, we introduce the fictitious temperatures:

$$\theta = T \cdot F\left(\frac{\hbar c \sigma}{k T}\right).$$

Equation (5) can then be written

$$T_{\odot}(\sigma) = \frac{1}{2} \frac{\hbar c}{k} \sigma + \frac{b_{\odot}(\sigma)}{b_{sky}(\sigma)} \left( 1 + \frac{1}{\tau^2(\sigma)} \frac{\Delta\omega}{\omega} \right) \cdot \left[ -\theta_B - \Delta\theta \frac{1 - \tau(\sigma)}{\tau(\sigma)} \right] \quad (6)$$

with  $\Delta\theta = \theta_B - \theta_a$ .

If this quantity vanishes, we see that it is not necessary to know the atmospheric absorption. In fact, everything takes place as if the atmosphere were a filter incorporated in the apparatus. In practice,  $\Delta\theta$  can be as large as 50 to 70 °K, because the apparatus is at -10° or -20 °C, while the atmosphere can be at -50 °C at the altitude of the flight. However, the spectra  $b_{\odot}(\sigma)$  and  $b_{sky}(\sigma)$  used for this measurement are analyzed at low resolution (5 cm<sup>-1</sup>), which is equivalent to replacing the true transmission spectrum by its convolution with the instrumental profile. Although the water vapor lines are saturated, they are narrow (Turon-Lacarrière and Verdet, 1968). The spectra from the third flight (Fig. 18), to be presented below, show a maximum depth on the order of 10% at 0.5 cm<sup>-1</sup> resolution, equivalent to 1% at the resolution actually used. Thus we see that the correction term  $\Delta\theta(1 - \tau)/\tau$  will always be less than 0.5 °K, compared to some 250 °K for  $\theta_B$ . Neglecting the correction term produces a relative error no greater than 0.2% in  $T_{\odot}$ , much less than the uncertainties we shall discuss below. Therefore we shall use Eq. (6) in the simplified form:

$$T_{\odot}(\sigma) = \frac{1}{2} \frac{\hbar c}{k} \sigma - \frac{b_{\odot}(\sigma)}{b_{sky}(\sigma)} \left( 1 + \frac{1}{\tau^2(\sigma)} \frac{\Delta\omega}{\omega} \right) \cdot T_B \cdot F\left(\frac{\hbar c \sigma}{k T_B}\right). \quad (7)$$

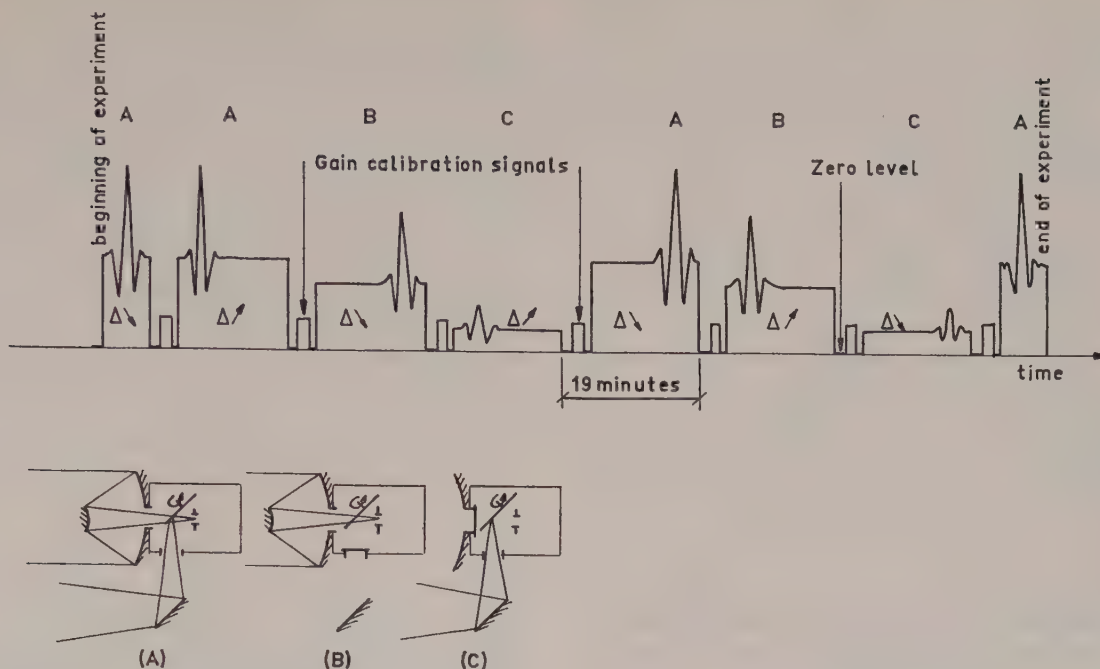


Fig. 12. Program of the first flight. A, B, and C are alternated: A Sun with compensation for sky background, B Sun without compensation, C sky compensation alone

#### b) Remarks

1) It is much less legitimate to neglect the correction for atmospheric absorption when calibrating with a laboratory black body. However, the maximum effect at the center of the absorption bands, broadened by the instrumental profile, is only 1%. This, too, can be neglected in view of the present accuracy of the measurements.

2) The emission of the filters requires the same sort of calculation, to the extent that their temperature can be different from that of the rest of the apparatus. However, we have avoided this possibility by beginning our measurements with the sky background.

### VII. Preliminary Flights

#### 1. The First Flight

The experiment was launched for the first time on June 24, 1967, from the Gap-Tallard base (Hautes-Alpes). Two hours of flight had been planned, to record seven interferograms of which six would be of maximum resolution, lasting 19 minutes each. The program is outlined in Fig. 12.

Because of a change in temperature during the ascent, a servomechanism in the detection circuit exceeded its range of stability, thus reducing the sensitivity of the system by a factor of about 20. The signal-to-noise ratio became too small: 50 on the solar interferograms, and 5 on the gain calibration signals. Consequently, the information deduced from these interferograms is not very trustworthy.

Nevertheless, a preliminary publication of the results (Gay *et al.*, 1967) reported a rather low mean observed temperature of around  $3400^\circ\text{K} \pm 300^\circ\text{K}$ , which we increased by 10% to correct for absorption by water vapor. The amount of water vapor had been estimated in a purely theoretical fashion which was, as it turned out after the third flight, entirely wrong.

In making this estimate, we compared the mean levels of the solar interferograms — that is, the total energies — with the mean levels of the interferograms of the laboratory calibration, using the signal of the standard lamp. The same method, applied to the two sky interferograms (or to the differences between the solar interferograms with and without compensation), implied a temperature on the order of  $270^\circ\text{K} \pm 30^\circ\text{K}$  for the experiment package, which seemed to indicate a satisfactory consistency in the measurements. It

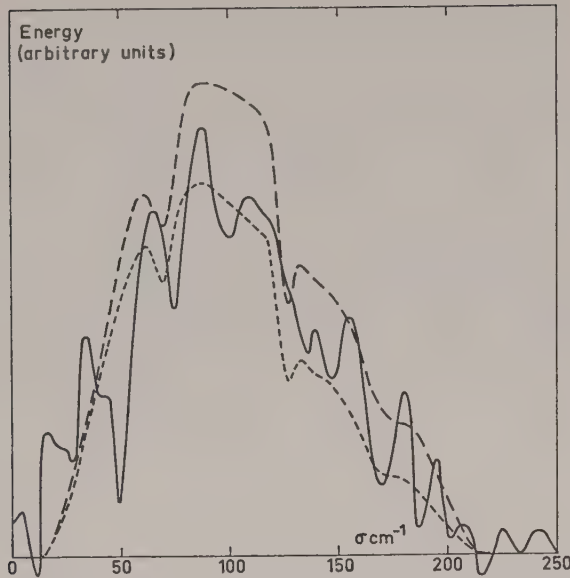


Fig. 13. Comparison of the first solar spectrum from the flight Helios I with a black body reduced to a Rayleigh-Jeans approximation

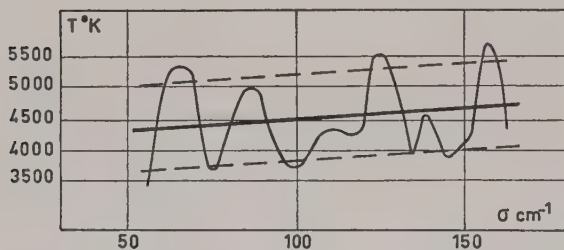


Fig. 14. Temperature of the Sun, derived from the first spectrum of the flight Helios I. The solid line indicates the mean slope of the function  $T_{\odot}(\sigma)$ . The dashed lines indicate the range of uncertainty

was, in fact, this conclusion which led us to use the radiation of the apparatus towards the sky as a second, independent calibration procedure during the succeeding flights.

Since then, we have realized that the sky background is not received in a solid angle identical with that of the Sun, but rather in a total solid angle  $S(\omega + \Delta\omega)$ ; this would imply a temperature for the sky that is much too low.

Therefore we must conclude that the measurements referred to the laboratory calibration are totally inconsistent. The gain calibration must have varied, for reasons which are still not clear to us.

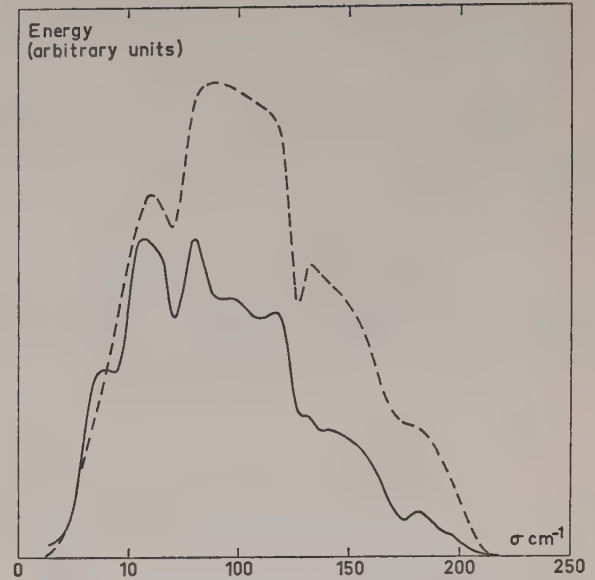


Fig. 15. Solar spectrum (solid line) derived from the flight Helios II, compared with the spectrum of a black body radiating according to the Rayleigh-Jeans law (dashed line). Note the intense absorption caused by the frost which formed on the telescope

It is still possible to attempt a direct comparison with the sky background, now that we know the beam corrections and the reflection coefficients of the mirrors on the optical path in the direction of the sky. This comparison implies a mean temperature of 4500 °K, with an uncertainty of a good 500 °K. On the other hand, a low-resolution reduction of the best of the six interferograms does not reveal any important differences between the profile of the solar spectrum and that of a black body, derived from the laboratory calibrations and reduced to a Rayleigh-Jeans approximation (Fig. 13).

On examining the mean slope of the curve  $T_{\odot}(\sigma)$  (Fig. 14), derived from the preceding graph, one can distinguish a decrease in the solar temperature from one end of the spectrum to the other. This effect is, of course, very uncertain.

We summarize the results of the first flight as follows:

$$\begin{aligned} T_{\odot} &= 4300 \pm 500 \text{ °K at } 70 \text{ cm}^{-1}, \\ &= 4500 \pm 500 \text{ °K at } 100 \text{ cm}^{-1}, \\ &= 4700 \pm 500 \text{ °K at } 150 \text{ cm}^{-1}. \end{aligned}$$

## 2. The Second Flight

The results of the second flight were much more disappointing. A sudden downpour a few minutes before the point of no return in the launching operations caused frost on the surface of the mirrors. Thus we obtained a heavily absorbed spectrum, especially at the higher frequencies (Fig. 15). From this spectrum we could deduce only a lower limit to the temperature, around 2000 °K at the higher frequencies and around 3000 °K at the lower frequencies. To make matters worse, a breakdown in the programming interrupted the experiment at the first inversion of the interferometer, and did not allow us to wait for the probable disappearance of the frost under the influence of the solar radiation.

## VIII. The Flight of January 16, 1968

The third flight took place on January 16, 1968, from the base at Aire-sur-l'Adour. The equipment worked perfectly; the following interferograms were obtained:

| Interferogram | Central fringe                     | Pressure | Altitude |
|---------------|------------------------------------|----------|----------|
| Sky           | 11 <sup>h</sup> 53 <sup>m</sup> UT | 12.7 mb  | 28.7 km  |
| Sun 1         | 11 56                              | 13.2     | 28.4     |
| Sun 2         | 12 33                              | 20.0     | 25.5     |
| Sun 3         | 12 36                              | 21.4     | 25.0     |

The altitude decreased continuously in the course of the experiment, because of a leak in the balloon. The gondola performed perfectly, but pointing errors became noticeable by the end of the last interferogram (Fig. 2). The effect of these errors, which can be described by a sinusoidal function with a 15 s period, is to introduce periodic ghosts in the interferograms. The resulting effect on the spectra is a perturbation in the vicinity of 30 cm<sup>-1</sup>. The other frequencies of the spectrum are not affected.

As the result of an error in selecting the gain of the electronics, which must have been made before launching, the central fringe of the interferograms was saturated. The three central points of each central fringe are therefore inaccurate (Fig. 16). The effect of this saturation was corrected by an iteration procedure, in the following manner: a preliminary spectrum was calculated from an interferogram which had been corrected approximately, making use of the fact that the rate of interference in our

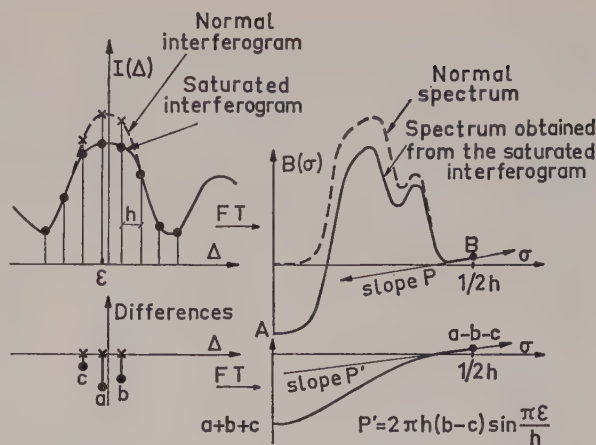


Fig. 16. Effect of the saturation of the central fringe, and possibilities for correcting it

interferometer is almost 100% at the wavelengths in question. The spectrum thus obtained is not identical with the base-line at its extremities. However, the difference is small enough (less than 10% of the maximum value of the spectrum) not to have a measurable effect on the position calculated for the zero path-difference. This is verified by the constancy (to within 0.2 μ) of the value found for ε at each step of the iteration. Let a, b, and c be the residual differences from the true values at the perturbed points, for the path differences ε, ε + h, and ε - h, respectively. Their effects on the calculated spectrum can be represented by the function:

$$\cos 2\pi\sigma\epsilon [a + (b+c)\cos 2\pi\sigma h] - (b-c)\sin 2\pi\sigma h \sin 2\pi\sigma\epsilon.$$

We know from the calibration spectra that there should not be any energy outside the interval between 25 cm<sup>-1</sup> and 220 cm<sup>-1</sup>. Thus the values of the calculated spectrum outside this range determine a, b, and c.

- 1) For σ = 0 we measure a + b + c = A;
- 2) For σ = 1/2h we measure (a - b - c) cos(πε/h) = B;
- 3) The slope P of the spectrum in the vicinity of

σ = 1/2h provides a third equation: P = 2πh(b - c) sin(πε/h).

The value of ε is given by the calculation for zero path-difference, starting with the above correction.

The constancy of the successive values found for ε makes the calculation converge very quickly (three iterations). The errors due to this restoration can be no greater than 1% at the center of the spectrum.

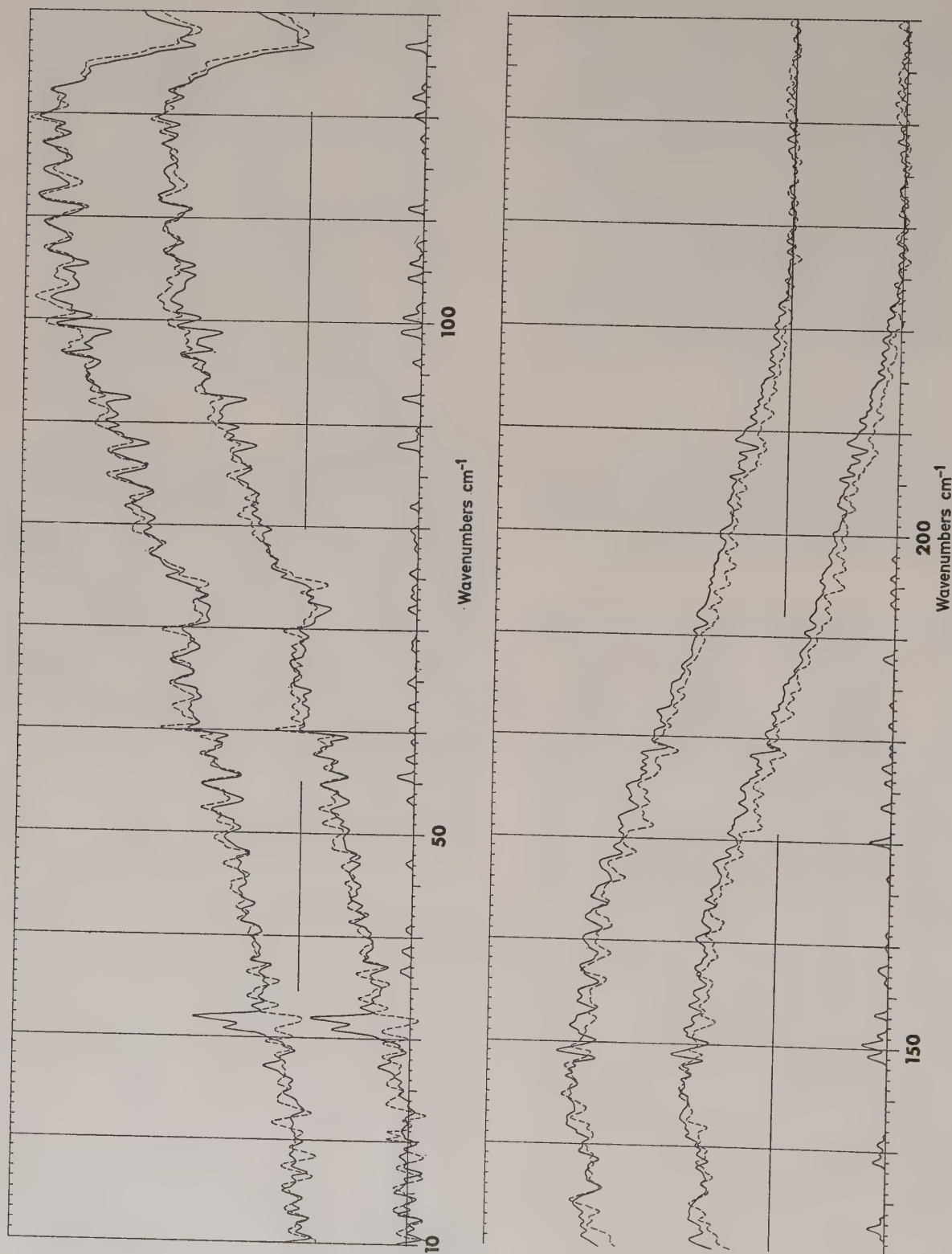


Fig. 17. First spectrum (dashed line) and second spectrum (solid line) from the flight Helios III, after apodizing ( $\Delta\sigma = 0.5 \text{ cm}^{-1}$ ). Above, we show the spectrum before correction for the channels, which are clearly visible near the center; and below, the spectrum corrected for these channels. The water-vapor lines are more distinct in the latter case. But the correction can cause a modification of their apparent intensity

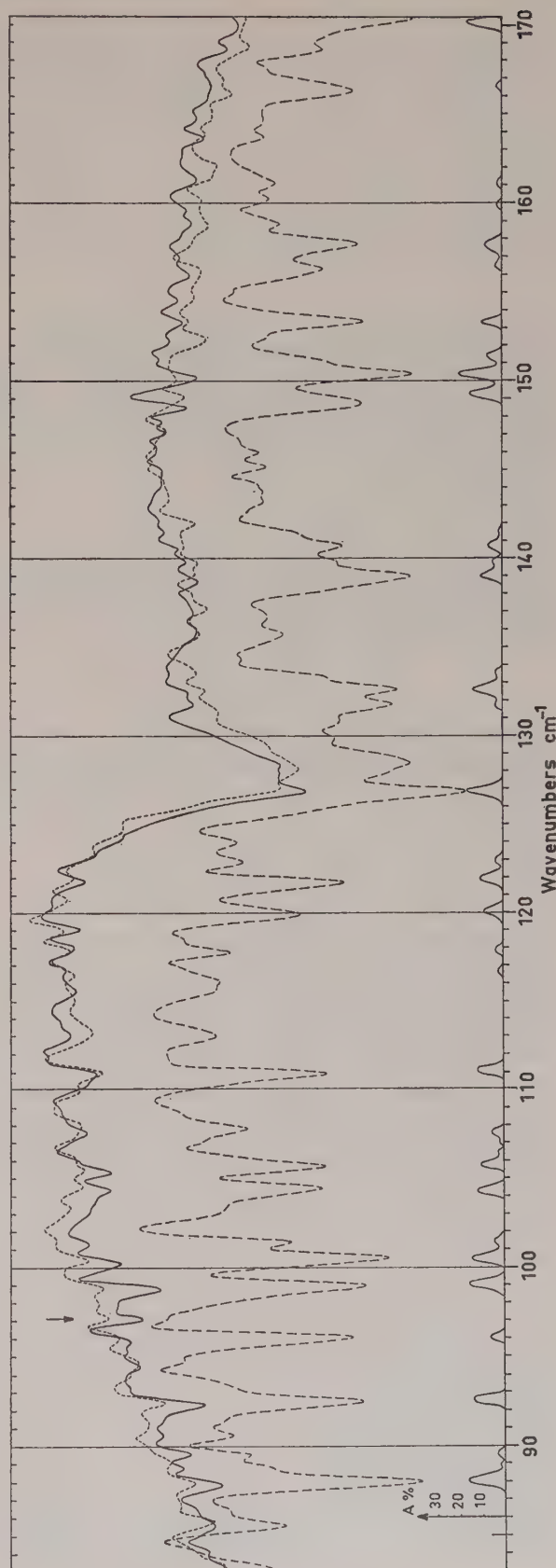
The spectrum is also affected by interference in the entrance window of the pneumatic detector, a plane-parallel quartz window. The result is a channel spectrum whose period is  $2.5 \text{ cm}^{-1}$  (Fig. 17), and whose amplitude reaches 10% of the mean level. This corresponds to an isolated, well-defined pattern in the interferogram, far from the central fringe, which is not difficult to eliminate (Fig. 18).

The spectra corrected in this manner are presented in Figs. 7, 17, and 18. The resolution is  $2.5 \text{ cm}^{-1}$  for the sky spectrum (Fig. 7), and  $0.5 \text{ cm}^{-1}$  for the solar spectra, after apodizing with the function  $(1 - \Delta/\Delta_{\text{max}})^2$  (Figs. 17 and 18). The signal-to-noise ratio is about 1000 for the solar interferograms and 100 for the sky interferogram, in agreement with what we had estimated from the performance of the ONERA pneumatic detector with a one-second integration step. The mean signal-to-noise ratio for each solar spectrum obtained in 20 minutes is 50 per frequency interval of  $0.5 \text{ cm}^{-1}$ , and 150 if we restrict ourselves to a resolution of  $5 \text{ cm}^{-1}$ . The signal-to-noise ratio is 25 for the sky spectrum, with a resolution of  $5 \text{ cm}^{-1}$ . This resolution was used for all comparisons between spectra, with a view to the calibration (Figs. 19 and 20).

## IX. Results Concerning the Atmospheric Absorption

The quantity of precipitable water was determined by comparing the equivalent widths of nine water-vapor lines, identified with certainty in the spectra Sun 1 and Sun 2 (Fig. 18), with the equivalent widths given by a theoretical model (Turon-Lacarrière, 1967) for physical conditions roughly similar to those of the flight (altitude = 30 km, atmospheric pressure = 10 mb, quantity of precipitable water in the vertical direction =  $0.67 \mu$ , zenith distance = 0). The equivalent widths grow as the square root of the product of the abundance and the atmospheric

Fig. 18. Same spectra as before, corrected for channels. At the bottom is drawn the theoretical absorption spectrum of water vapor for  $0.67 \mu$  of precipitable water, at  $0.5 \text{ cm}^{-1}$  resolution. (Absorption, A, increases towards the top.) The intermediate water-vapor spectrum was obtained in a vacuum chamber, with the same resolution as that used in the flight. Note the line at  $97.2 \text{ cm}^{-1}$  on the solar spectra (marked with an arrow). It is probably due to an atmospheric component other than water vapor. The theoretical lines marked with a dash were used to determine the quantities of water



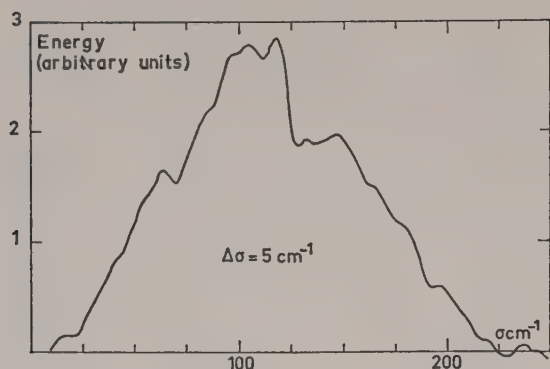


Fig. 19. Spectrum of the radiation of the experiment package towards the sky, at  $5 \text{ cm}^{-1}$  resolution, used for temperature calculations

pressure, for the lines are narrow and saturated. From the accompanying Table 1 we can deduce the amounts of water along the line of sight:

$$\text{Sun 1: } 0.056 \pm 0.017 \mu,$$

$$\text{Sun 2: } 0.20 \pm 0.06 \mu.$$

Taking into account the mean zenith distance of  $67^\circ$ , we arrive at the following quantities of precipitable water:

$$0.022 \pm 0.006 \mu \text{ above } 28.4 \text{ km},$$

$$0.077 \pm 0.015 \mu \text{ above } 25.0 \text{ km}.$$

These results indicate a scale height of  $2.5 \pm 0.5 \text{ km}$  for the distribution of water vapor in the stratosphere, in perfect agreement with the measurements made by radio sounding out to 20 km (Picherit, 1969).

These results are in satisfactory agreement with those obtained by Sissenwine *et al.* above California ( $40^\circ \text{ N}$  latitude), cited by Kuiper *et al.* (1967); they reported  $0.1 \mu$  at 25 km and  $0.05 \mu$  at 30 km, implying a scale height of 3.5 km. On the other hand, our results are in disagreement with those of earlier

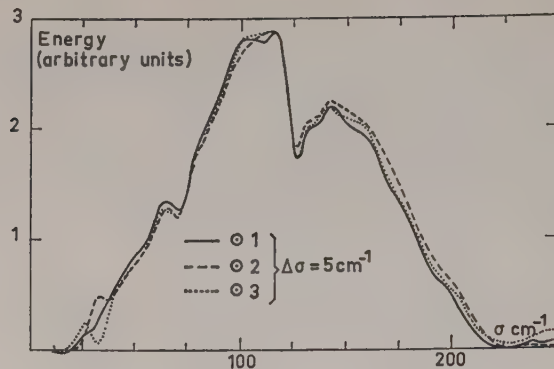


Fig. 20. Solar spectra 1, 2, and 3 from the flight Helios III, at the resolution of  $5 \text{ cm}^{-1}$  used for the temperature calculations. Note the strong perturbation at  $32 \text{ cm}^{-1}$  on spectra 2 and 3: it is due to the modulation of the continuum level by the oscillations of the gondola. Of the three spectra, No. 2 was most successfully corrected for saturation effects; but it is the weakest piece of evidence for the temperature calculations

experiments (Zander, 1966; Houghton, 1963; Murcray *et al.*, 1962) which indicated a higher humidity, perhaps due to the degassing of the apparatus.

Thus we see that the mean absorption, integrated from 70 to  $130 \text{ cm}^{-1}$ , is less than 1% at an altitude of 25 km, and falls to 0.3–0.4% at 28.4 km. Normal flights are made at a pressure of around 10 mb, that is, at an altitude of 30 or 31 km. Therefore we can reasonably expect an absorption of around 0.1% — or even less, if we observe farther from the horizon. These encouraging results may be partly attributable to seasonal effects, for the stratosphere is certainly drier in the winter than in the summer.

The degassing of the apparatus and of the balloon envelope does not seem to be very troublesome. Perhaps it takes place very rapidly during the ascent (1 h 30 m) or during the stabilization phase (30 m). The degassing is obviously accelerated by the solar

Table 1. Table of the water-vapor lines used in measuring the quantity of precipitable water above the balloon

| Frequency of the line<br>used in $\text{cm}^{-1}$ (indicated by a<br>vertical bar on Fig. 18). | 88   | 92.5 | 99   | 100.5 | 104.3 | 105.8 | 122  | 126.8 | 150.5 |
|------------------------------------------------------------------------------------------------|------|------|------|-------|-------|-------|------|-------|-------|
| Ratio of the measured and<br>model equivalent widths                                           |      |      |      |       |       |       |      |       |       |
| Sun                                                                                            | 0.36 | 0.55 | 0.25 | 0.36  | 0.24  | 0.21  | 0.28 | 0.39  | 0.20  |
| Sun                                                                                            | 0.70 | 1.13 | 0.88 | 0.58  | 0.52  | 0.62  | 0.60 | 0.95  | 0.75  |

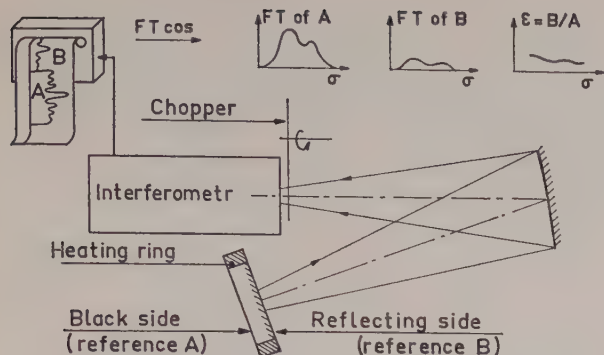


Fig. 21. Principle of the measurement of the emission coefficient of a reflecting material

radiation, which makes it difficult to extrapolate these results to a nocturnal flight.

These considerations do not detract from the conclusion that projects for astronomical observations in the far infrared from stratospheric gondolas are very well-founded. We can hope to find apparent radiation temperatures of the atmosphere (the most troublesome consequence of absorption) of less than 1 °K, on the average, in the range from 70  $\text{cm}^{-1}$  to 130  $\text{cm}^{-1}$  — the region where water vapor absorption is greatest. This effect can, moreover, be greatly reduced by the method of compensation for radiation towards the sky background. The procedure would be analogous to that described in this article, but with a more rigorous symmetry of the two tracks, obtained by using a cat's-eye interferometer (Gay *et al.*, 1970).

*Remark.* An absorption line at  $97.2 \pm 0.1 \text{ cm}^{-1}$  appears on both spectra (Fig. 18). Its origin has not yet been determined. The absorption is probably caused by a component of the atmosphere, for the feature increases in depth in going from the first to the second spectrum. However, the difference is not much above the noise level, so that it is difficult to be certain of this effect.

## X. Brightness Temperature of the Sun

We shall present only the results of the third flight (January 16, 1968). The first spectrum (Sun 1 — Fig. 20), obtained at the highest altitude, was calibrated by the two methods described in § VI (Eqs. 4 and 7). No correction for atmospheric absorption and emission was necessary because, considering the quantity of water measured, these corrections would have been much smaller than the errors of observation.

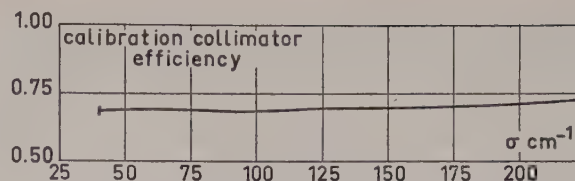


Fig. 22. Total efficiency of the calibration collimator

We believe that we have eliminated the principal systematic errors in the two calibration methods. In the case of calibration with a laboratory black body, the principal correction arises from absorption by the mirrors of the collimator. This absorption was determined from the emission of an identical sample of material, heated and compared with an absorbing material at the same temperature: sand, whose emission coefficient is very nearly unity, demented with vacuum grease to the face opposite the polished surface (Fig. 21). The error in  $\varrho(\sigma)$  is small, even though the relative error in the emission coefficient is rather large.

The transmission of the collimator determined in this way, and corrected for the effect of the temperature (80 °C) on the absorption coefficient (Bramson, 1968), is 0.70 at about 100  $\mu$ , with three reflections (Fig. 22).

In the case of calibration on the sky background, we took into account the fact that the temperature of the telescope — and therefore its transmission — and its geometry were different during the flight and during the laboratory measurement. This affected the ratio between the total extent of the beam received from the sky, and the extent of the beam received after reflection from the telescope mirrors. In both cases, a systematic error — no doubt rather small, but difficult to estimate — can also arise from the fact that the filters (principally the black polyethylene filter) were raised to a higher temperature during observation of the Sun than during calibration on the sky (which preceded setting on the Sun), or during the laboratory calibration. The possible error due to variations in the emission of the black polyethylene filter is completely negligible (much less than 1% at all frequencies). On the other hand, possible temperature variations in the absorption of black polyethylene can produce an error, for the solar flux is not affected in the same way as the calibration flux. In practice, this phenomenon can play a role only in the polyethylene absorption band at 125–130  $\text{cm}^{-1}$  and beyond 150  $\text{cm}^{-1}$ . The effect is certainly quite negligible below 100  $\text{cm}^{-1}$ , where

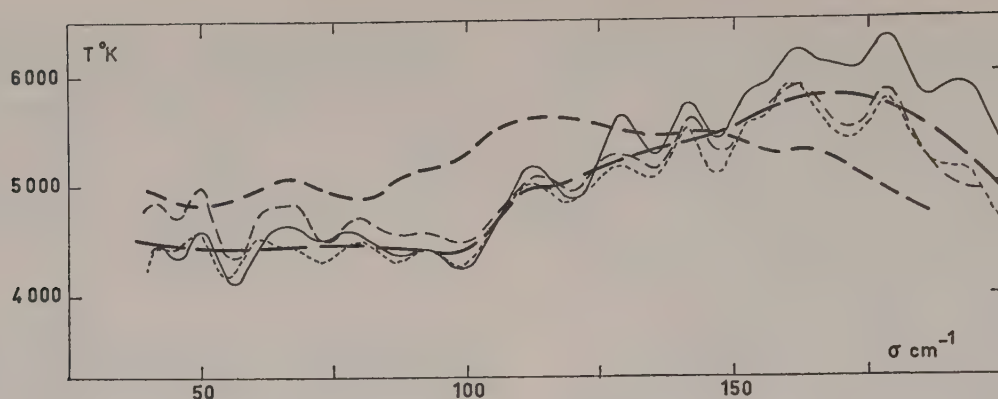


Fig. 23. Results of the solar temperature calculations using the different calibration procedures.

--- 1st spectrum } The dispersion of these three curves gives an idea of the  
 --- 2nd spectrum } uncertainty due to the saturation of the central fringe.  
 .... 3rd spectrum } Measurements referred to laboratory  
 --- average of the three preceding spectra, smoothed to a resolution of  $25 \text{ cm}^{-1}$ . } calibrations  
 --- first spectrum, referred to the sky background (smoothed to a resolution of  $20 \text{ cm}^{-1}$ )

the absorption coefficient of polyethylene is very small.

We give below an estimate of the errors in the determination of the temperature of the Sun. The noise errors are r.m.s. values.

#### Errors Common to the Two Calibration Procedures

|                                                                       |      |
|-----------------------------------------------------------------------|------|
| Restoration of the saturated central fringe (at a maximum $100 \mu$ ) | 1%   |
| Instability and non-linearity of the gain                             | 1.5% |
| Atmospheric absorption (on the first spectrum)                        | 0.3% |
| Noise in the solar spectrum (signal/noise $\cong 150$ )               | 0.7% |

#### Errors Pertaining Only to the Laboratory Calibration

|                                                                                                                    |      |
|--------------------------------------------------------------------------------------------------------------------|------|
| Error in the transmission of the collimator                                                                        | 2%   |
| Noise in the calibration spectra (integration over 25 spectra, resolution $5 \text{ cm}^{-1}$ , signal/noise = 60) | 1.5% |

#### Errors Pertaining Only to the Sky Calibration

|                                                                                   |    |
|-----------------------------------------------------------------------------------|----|
| Error in the temperature of the interferometer box                                | 2% |
| Noise in the sky spectrum (resolution $5 \text{ cm}^{-1}$ , signal/noise = 25)    | 4% |
| Noise in the measurement of the extent of the extraneous beam (signal/noise = 30) | 3% |

From this summary we have derived the following table, giving the errors in various spectral regions.

| $\sigma$             | Laboratory calibration              |                             |                      | Sky Calibration                     |                             |                      |
|----------------------|-------------------------------------|-----------------------------|----------------------|-------------------------------------|-----------------------------|----------------------|
|                      | Noise<br>per<br>$5 \text{ cm}^{-1}$ | "System-<br>atic"<br>Errors | Total                | Noise<br>per<br>$5 \text{ cm}^{-1}$ | "System-<br>atic"<br>Errors | Total                |
| $50 \text{ cm}^{-1}$ | $180^\circ \text{K}$                | $410^\circ \text{K}$        | $590^\circ \text{K}$ | $450^\circ \text{K}$                | $410^\circ \text{K}$        | $860^\circ \text{K}$ |
| 70                   | 90                                  | 270                         | 360                  | 220                                 | 270                         | 490                  |
| 100                  | 60                                  | 230                         | 290                  | 150                                 | 230                         | 380                  |
| 150                  | 90                                  | 270                         | 360                  | 220                                 | 270                         | 490                  |
| 180                  | 180                                 | 410                         | 590                  | 450                                 | 410                         | 860                  |

By "systematic" errors, we mean all the sources of error whose effects are not random, but which we can define only by a maximum value.

Figure 23 shows the results obtained by the two calibration procedures. The internal agreement of the measurements referred to the vacuum-chamber calibrations is good. If we smooth over frequency intervals greater than  $5 \text{ cm}^{-1}$ , the error decreases; but it never becomes less than about  $250^\circ$ , or 5%. This lower limit is due to the systematic errors, which do not decrease with the resolution.

Between  $50$  and  $100 \text{ cm}^{-1}$ , the results are in good agreement with the predictions of the BCA model, shown in Fig. 24. Agreement with the URP model (Utrecht Reference Photosphere: Heintze, Hubenet, de Jager, 1964) is less satisfactory, for this model predicts  $5000^\circ \text{K}$  at about  $50 \text{ cm}^{-1}$ , and  $4800^\circ \text{K}$  around  $100 \text{ cm}^{-1}$ . In particular, although our tem-

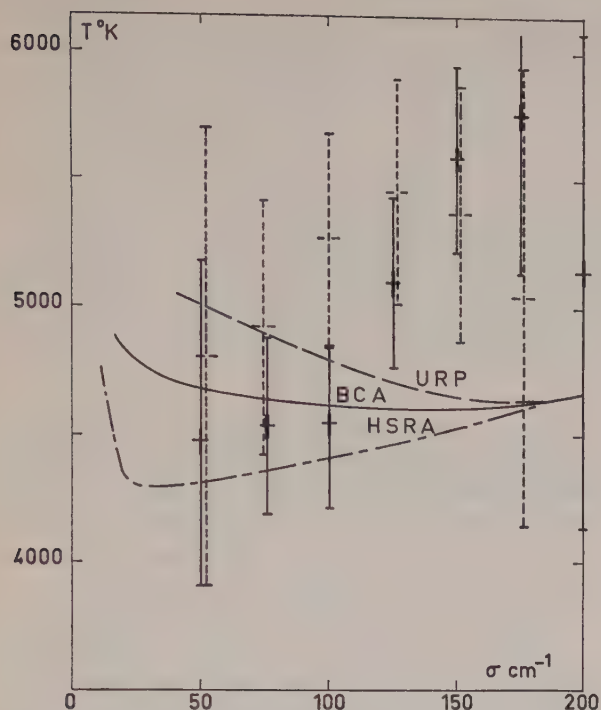


Fig. 24. Comparison of the results with the "Utrecht Reference Photosphere" (URP), the "Bilderberg Continuum Atmosphere" (BCA), and the "Harvard-Smithsonian Reference Atmosphere" (HSRA) models.  $\div$  measurements referred to the sky background,  $+$  measurements referred to the laboratory calibrations

perature values are not precise, our measurements do show that the temperature in this layer is certainly uniform to within 100 °K, for the systematic errors affect measurements throughout this spectral range in the same way. It follows that the slope of the temperature profile in this region agrees better with the recent model of Gingerich (1969), called the "Harvard-Smithsonian Reference Atmosphere" or HSRA, than with the BCA model.

We cannot be sure that the temperature increase around 150  $\text{cm}^{-1}$  is real, but it is not unlikely. To explain this, we would have to assume the existence of an absorbent that is especially effective at 160  $\text{cm}^{-1}$ , in the interval 100 to 200  $\text{cm}^{-1}$ , and whose optical depth unity corresponds to the altitude at which the temperature reaches 5600 °K — that is, 590 km in the BCA model, or 540 km in Gingerich's latest model.

A possible explanation for this temperature increase lies in the translation spectra of atoms or ions whose collision, giving rise to a transitory pseudo-molecule with a large induced dipole moment, causes

the translation energy of the particles in collisions to be radiated away — hence the name "translation spectrum" (Bosomworth and Gush, 1965b). The theory has yet to be worked out for the temperature, pressure, and composition of the chromosphere. But if the existence of such an absorbent were confirmed, it would oblige us to reconsider the interpretation of the limb-darkening measurements at frequencies around 200  $\text{cm}^{-1}$ , which has essentially been based on the assumption that  $\text{H}^-$  is the only absorbent.

In order to ascertain the reality of this temperature increase, we proceeded on November 24, 1968, to launch another experiment for absolute spectrophotometry of the Sun, covering a spectral range (50  $\text{cm}^{-1}$  to 500  $\text{cm}^{-1}$ ) more extensive than that of the preceding flights. A partial reduction of the data from this second flight confirms the temperature anomaly reported here.

#### XI. Perturbations due to Oscillations of the Gondola: Description of a Possible Method of Measuring the Center-Limb Effect

A perturbation in the vicinity of the frequency 32  $\text{cm}^{-1}$  can be noticed on the three spectra of the third flight. It is to be found on both the high-resolution spectra (Figs. 17 and 18) and the low-resolution spectra (Fig. 20). The perturbation is quite visible on the last two spectra, but is barely above the noise level on the first spectrum. We have traced this effect to the modulation of the mean level of the interferogram caused by the oscillations of the gondola, which we recorded in the course of the experiment (Fig. 2).

The pointing-error oscillations are quite well represented, over a reasonable time interval, by a sinusoidal function of the time:

$$z = a + b \cos(2\pi \frac{t}{T} + \varphi), \quad (8)$$

where  $a$  is the permanent pointing error due to imperfections in the pre-launch regulation (the centering was performed to within one or two minutes of arc);  $b$  is the mean amplitude of the oscillations of the gondola during an interferogram near the central fringe; and  $\varphi$  is the phase of the oscillation, taking the origin of time at the passage through the central fringe. In measuring the effects of the oscillations, we shall use only the low-resolution spectra derived from the small section of the interferogram near the central fringe, where we can be sure of the phase stability. Since the path difference varies linearly at the rate of 20  $\mu$  per second, we can associate with the

Table 2. *Explanation in the text*

| No.<br>of spectra | Period of<br>pointing error<br>oscillations<br>s | Corresponding<br>frequency<br>cm <sup>-1</sup> | Frequency<br>measured<br>on spectra<br>cm <sup>-1</sup> | $\frac{s}{10} \cdot 10^{-3}$ | 2b (V)        | cos $\varphi$ | 2b cos $\varphi$ |
|-------------------|--------------------------------------------------|------------------------------------------------|---------------------------------------------------------|------------------------------|---------------|---------------|------------------|
| 1                 | 15.8                                             | 32.3                                           | 30 ± 3                                                  | - 3.2 ± 1.5                  | 0.080 ± 0.002 | - 0.6 ± 0.1   | - 0.048 ± 0.01   |
| 2                 | 16.8                                             | 31.8                                           | 31 ± 1                                                  | + 10.5 ± 1.5                 | 0.454 ± 0.020 | + 0.97 ± 0.03 | - 0.471 ± 0.03   |
| 3                 | 16.16                                            | 31.6                                           | 33 ± 1                                                  | - 15.2 ± 1.5                 | 0.637 ± 0.020 | - 0.85 ± 0.1  | - 0.542 ± 0.07   |

period  $T$  – approximately 16 s – the wavenumber  $\sigma_0 = 32 \text{ cm}^{-1}$ , at which the perturbation in the spectrum appears (Table 2).

Since the solar image overflows the field diaphragm, effects caused by the pointing errors can appear only if the illumination is not uniform over the image area covered by the range of the oscillations. In carrying out the calculations, we shall assume that the illumination is distributed with radial symmetry about the center of the solar image.

Let  $E(r)$  be the function describing this illumination, integrated over all the observed spectral frequencies. The continuum level of the interferogram, in the absence of pointing errors, is represented by the integral of the illumination over the area of the field diaphragm, whose radius is  $r_0$ :

$$\phi_0 = 2\pi \int_0^{r_D} E(r) r dr = \pi r_D \bar{E},$$

where  $\bar{E}$  is by definition the mean illumination.

This mean level is also the integral of the spectral distribution  $B(\sigma)$  deduced from the interferogram:

$$\phi_0 = \int_{\sigma} B(\sigma) d\sigma = S$$

where  $S$  is the surface area of the spectrum in consistent units.  $B(\sigma)$  is the integral over the diaphragm of  $E_{\sigma}(r)$ , the spectral illumination density of the image:

$$B(\sigma) = 2\pi \int_0^{r_D} E_{\sigma}(r) r dr$$

which includes the integral relation

$$E(r) = \int_{\sigma} E_{\sigma}(r) d\sigma.$$

It can be shown, by expanding in a Taylor series, that if the center of the solar image is displaced from the center of the diaphragm by a small amount  $z$ , the mean level of the interferogram is perturbed in the second order, to a first approximation, according to the formula:

$$\phi(z) = \phi_0 + \frac{\pi}{2} z^2 r_0 E'(r_D).$$

In view of the form of  $z$ , given in Eq. (8), the supplementary signal thus added to the interferogram appears in the spectrum as a monochromatic pattern whose integrated surface area is

$$\begin{aligned} \pi a b \cos \varphi r_D E'(r_D) & \text{ at frequency } \sigma_0, \\ \frac{\pi}{4} b^2 \cos(2\varphi) r_D E'(r_D) & \text{ at frequency } 2\sigma_0. \end{aligned}$$

We present in Table 2 the different values measured for  $\cos \varphi$  and for  $b$  (in voltage of the offset signal, whose angular equivalent will be specified below). We also give the ratio  $s/S$  of the surface area of the perturbation, at frequency  $\sigma_0$ , to the total surface area of the spectrum.

We see in Fig. 25 that the relation

$$\frac{s}{S} = \left( \frac{a E'(r_D)}{r_D \bar{E}} \right) b \cos \varphi$$

is well satisfied. We can derive the value of the coefficient

$$\frac{a E'(r_D)}{r_D \bar{E}} = \frac{1}{\Sigma} (52 \pm 4) \cdot 10^{-3} (\text{minutes})^{-1}$$

where  $\Sigma$  is the sensitivity of the solar sensor in minutes per volt. We must know the value of the permanent pointing error,  $a$ . To determine it, we graph the setting errors (in Volts) as a function of the final decrease in the mean level (Fig. 26), and we proceed by the method of diameters. The uncertainty is rather great, because of the small number of points on one of the branches of the curve. We obtain:

$$a = -0.18 \pm 0.03 \text{ V},$$

whence

$$\left[ \frac{1}{r} \frac{d}{dr} \left( \frac{E(r)}{\bar{E}} \right) \right]_{r=r_D} = -\frac{1}{\Sigma^2} (0.29 \pm 0.07).$$

At this point, our manipulation of the results is stalled by the uncertainty in the value of  $\Sigma$ , the sensitivity of the gondola's solar sensor. It has not, in fact, been possible to bring into agreement the indications of the pitch offset given by the two telemetry tracks. For want of a better solution, we

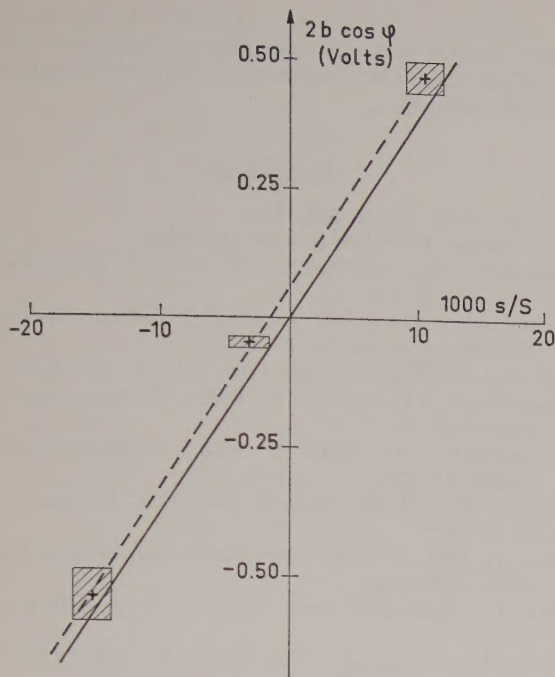


Fig. 25. Explanation in the text

shall use the value indicated by the non-amplified track (called the "coarse sensor" track), which yields:

$$\frac{1}{E} \frac{dE}{dr} = 2.4\% \text{ per arc min, for } r = r_D = 13.$$

We have compared this slope with that caused by diffraction. This required us to make an explicit analysis of the diffraction effects near the solar limb, taking into account the spectral distribution and the effects of the secondary mirror of the telescope and of its support tripod (Gay, 1970). It can be shown that the diffraction can account for a slope of only  $-1\%$  per arc min. The remainder can easily be explained by defects in the telescope, which was originally designed only as a light-collector. These defects could easily account for a slope of  $-5$  to  $-10\%$ , much greater than that actually measured. Thus we are completely in the dark as to the very existence of the anticipated center-limb effect. However, these considerations have led us to conceive of a method for measuring the center-to-limb profile from a balloon. For if we had chosen a diaphragm of smaller radius and a telescope of better quality, we would have eliminated any slope in the profile except that due to the center-limb effect. Let us define in the usual manner

$$\sin \theta = r_D/r_\theta, \quad \cos \theta = \mu.$$

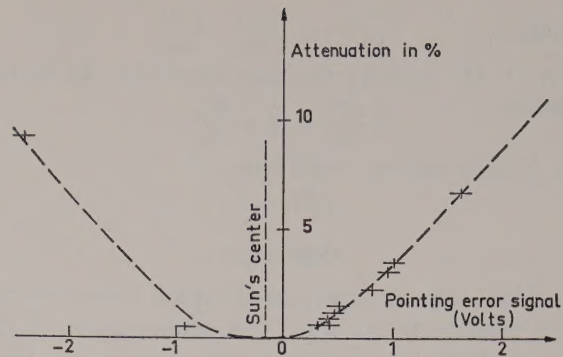


Fig. 26. Explanation in the text

Replacing the source function in the far infrared by the Rayleigh-Jeans approximation, we measure a brightness temperature at wavelength  $\lambda$  — for a value of the parameter  $\mu$  determined by the radius of the diaphragm — according to:

$$T_\lambda(\mu) = \int T(\tau_\lambda) e^{-\frac{\tau_\lambda}{\mu}} \frac{d\tau_\lambda}{\mu} \cong T(\tau_\lambda \cong \mu).$$

And from the offset oscillations we determine a radial slope

$$\frac{\partial T_\lambda}{\partial r} = -\frac{\sqrt{1-\mu^2}}{\mu} \frac{\partial T_\lambda}{\partial \mu},$$

where the derivative with respect to  $\mu$  is obtained by differentiating Eq. (9), and then integrating by parts. There remains only the unintegrated part, which can properly be estimated by the Barbier-Eddington approximation (with  $\tau_\lambda \frac{\partial T}{\partial \tau_\lambda}$  replacing the source function in the equation of transfer):

$$\begin{aligned} \frac{\partial T_\lambda}{\partial \mu} &= \frac{1}{\mu} \int e^{-\frac{\tau_\lambda}{\mu}} \left( \tau_\lambda \frac{\partial T}{\partial \tau_\lambda} \right) \frac{\partial \tau_\lambda}{\mu} \cong \frac{1}{\mu} \left[ \tau_\lambda \frac{\partial T}{\partial \tau_\lambda} \right]_{\tau_\lambda=\mu} \\ &= \left( \frac{\partial T}{\partial \tau_\lambda} \right)_{\tau_\lambda=\mu} \end{aligned}$$

This enables us to derive the temperature gradient for all the altitudes corresponding to the wavelengths at which we have measured the derivative of the radial profile.

Finally, examination of the variations of  $T_\lambda$  and of the profile  $\frac{\partial T_\lambda}{\partial \mu}$  will enable us to specify the absorption law in the layer under consideration. Let us suppose, for example, that the absorption coefficient can be written in the form

$$k_\lambda(p_e, T_e, c) = f(\lambda) \cdot g(p_e, T_e, c),$$

where  $p_e$ ,  $T_e$ , and  $c$  represent the physical conditions at a point of the chromosphere (electron pressure, electron temperature, and composition). It can be shown that the measurements must satisfy the

relation: 
$$\frac{\partial T_{\lambda}}{\partial \lambda} = \mu \cdot \frac{\partial T_{\lambda}}{\partial \mu} \cdot \frac{f'(\lambda)}{f(\lambda)}$$

Thus if  $H^{-}$  is really the only absorbent, we should obtain

$$\lambda \frac{\partial T_{\lambda}}{\partial \lambda} = 2 \mu \frac{\partial T_{\lambda}}{\partial \mu}$$

for in that case we would have

$$f(\lambda) = \lambda^2.$$

### Conclusion

This series of experiments, which represents the first attempt to make a direct determination of the photospheric temperature in the region  $\tau_{5000} = 0.01$ , does not enable us to choose between the BCA model and the HSRA model and does not, despite the rather surprising temperature rise around  $150 \text{ cm}^{-1}$ , reveal any important anomaly in the photosphere. Our experiments thus join the partial results provided by the study of the brightness distribution at the solar limb at around  $20 \mu$  (Léna, 1968), and in the vacuum ultraviolet (Bonnet and Blamont, 1968). A comparison with infrared measurements in adjacent spectral regions (Beer, 1966; Koutchmy and Peyturaux, 1968; Eddy *et al.*, 1969) is planned, using the results of the November, 1968 flight for the higher frequencies, and those of the flight planned for June, 1969, for the lower frequencies. The equipment launched in these later flights is an improved instrument, remedying the defects of the experiment described in this article. The data obtained during this flight are being reduced.

The weakness of the atmospheric absorption above 28 km confirms the advantage of balloon flights for exploring the spectral region  $50 \mu - 300 \mu$ , and encourages our group to embark upon more complicated projects — such as the measurement of the solar limb-darkening between 50 and  $200 \mu$ , using the method described in the last section of this paper; high-resolution solar spectroscopy between 20 and 300 microns ( $0.05 \text{ cm}^{-1}$ ); the temperature balance of Jupiter; and infrared spectroscopy of H II regions. All these projects are supported by the National Center for Space Studies (CNES).

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